Major Trends in Gravure Printed Electronics

By Donna Ariel Clark

Graphic Communication Department
College of Liberal Arts
California Polytechnic State University
June 2010

Abstract

Printing has become a mature industry, forcing printers to create new applications for their manufacturing process. One such application is printed electronics. The gravure printing process allows for incredible speed and exceptional quality for traditional graphic printing. Theoretically, this would be an ideal method for the commercial production of printed electronics. This study analyzes gravure's capabilities to produce a uniform conductive ink line and what to expect in the future of gravure printed electronics. Printed line properties such as line widening and scalloped edges were determined to impede gravure's ability to lay down a conductive ink line. Best results were achieved with high viscosity inks, high pressure, and a slow printing speed. Ink surface uniformity was also a problem due to ink dots created from the electromechanically engraved cells, thus increasing line resistance. In general, the gravure process needs to be substantially modified before a mass production of printed electronics can take place. Although it is unlikely that any specific printing process, will completely dominate the production of a single electronic product, gravure will be substantial portion of a hybrid electronic manufacturing process. Possible applications include low power devices, such as batteries or photovoltaics.

Table of Contents

Chapter 1 Introduction

Printed electronics is a new market for the graphic communication industry. Pairing traditional printing processes with conductive, metal-based inks allows for the production of electrically functional devices, known as printed electronics. Modifying traditional printing processes is a cost-efficient way to mass produce simple electronic devices. Printed electronics can be created using several of traditional print processes including screen printing, flexography, offset lithography, gravure, and inkjet. Each process has its own strengths and limitations in regard to the production of printed electronics, allowing each process to be the ideal method of production for a different range of products or layers.

Huge growth is expected in the market for printed electronics. Currently, applications for printed electronics include flexible displays, smart labels, photovoltaic devices, organic light emitting diode (OLED) displays, electronic memory and logic, and radio frequency identification (RFID) tags. For electronics to be printed successfully, high resolution is crucial. High resolution corresponds with high-quality graphics. With traditional printing, the human eye determines the quality of the printed piece. Microscopic gaps in ink flow are not an issue, as they are not visible to the viewer. However, when printing some electronics, resolution is an essential part of the structure and function of the printed piece. Continuous lines of metal-based ink are needed for conductivity and to ensure continuity throughout a circuit.

Electrical current is the rate of flow of electrons moving through an electrical conductor. These electrons carry an electrical charge. Solid, conductive metals, such as gold, copper and silver, contain free electrons. When an electrical force is placed on a conductive metal wire, the free electrons move in the direction of the force, creating an electrical current. The resistance of the electrical current depends on the thickness and length of the wire. In print, this translates to the width, ink height and length of the printed line. Thicker wires and longer wires allow for more substantial electric currents to flow through them.

The gravure printing process has the ability to produce extremely high quality images, and is the most cost-effective way to print long-run jobs among the other methods of commercial printing. Some common gravure printed products include wood laminates, printed flooring, wrapping paper, and high quality publications such as National Geographic. In gravure, a large steel cylinder is electroplated with copper and engraved with microscopic cells using either electromechanical or laser engraving. The cylinder is then electroplated with chrome to ensure that it will not wear down during print production. Low viscosity, or fluid, ink is held in a bath beneath the rotating gravure cylinder, filling the etched cells with ink. A blade is then used to scrape off any excess ink from the cylinder as it rotates. A roll, or web, of paper travels between the etched cylinder and an impression cylinder, using capillary action to transfer the ink from the cells onto the paper. In several cases, a process called electrostatic assist is used, where an electrostatic charge is added to the paper to help ensure that all of the ink is extracted from the cells on the etched cylinder and transferred to the substrate. Gravure has the capability to print a continuous image, allowing it to be a versatile printing process.

Using gravure for printing electronics is a cost-effective way to produce a large quantity of functional electronic devices. While still in its infancy, gravure printed electronics have the potential to become a major asset in the marketplace. This study asks the question: What are the major trends in gravure printed electronics? Companies are continuing to experiment with electronic applications that would be best suited for gravure printing, and several innovative ideas are beginning to emerge.

The future of gravure printed electronics most likely lies in the market for organic semiconductors and batteries. Organic semiconductors are used in the production of flexible LEDs and photovoltaics. While gravure is capable of printing extremely high quality graphics, it struggles to produce consistent straight lines. A large degree of control is needed over the size and shape of lines printed with conductive ink. The applications for gravure printed electronics might be limited due to this production constraint. Both the production of photovoltaics and batteries require a large-ink lay down to create a working product, which is a strength of the gravure process.

The purpose of this study is to determine the potential for printed electronics by the gravure printing process. Specific thicknesses of ink are needed for different amounts of electrical current to pass through conductive printed lines. Ink-height and width capabilities will be analyzed to determine if the gravure process is viable method for producing low frequency printed electronics, and to specify which applications gravure is best suited for.

Chapter 2 Literature Review

The gravure printing process is a cost-effective way to print long-run, high-quality jobs. Chrome-plated etched cylinders do not wear out as quickly as other forms of printing plates, so long-run jobs of over a million copies are possible without reimaging the cylinder. Gravure allows for the use of a variety of substrates, including thin films. The process is also capable of accepting a range of ink viscosities and can directly apply a variable ink film thickness to the substrate. This versatility allows gravure to be a preferable method for printing electronics. As the market for printed electronics expands, gravure technology also continues to advance and adapt to meet the needs of the market.

Gravure versus Inkjet Printing Technologies

Inkjet printing is currently the most studied form for producing lost-cost printed electronics. Inkjet printers include an inkjet head with many nozzles connected to a separate ink cartridge. These printers use a drop-on-demand technique where each nozzle moves back and forth depositing drops of ink that are about 50 microns wide (50 millionths of an meter) onto the substrate (Lawler). There are two types of drop-on-demand inkjet printers: thermal, or bubble jet, and piezoelectric. Thermal inkjet printers deposit ink from the nozzle by heating the ink until a bubble is formed, thus forcing a small drop of ink out from the nozzle. Piezoelectric inkjet printers use an electric charge which causes a piezo crystal to expand and change shape, pushing a droplet of ink out of the nozzle (Lawler).

While inkjet printers are ideal for researching printed electronics, their slow speed inhibits the process from being used as a high-volume, industrial production method for printed electronics. In a technical report published by the University of California, Berkeley entitled Gravure as an Industrially Viable Process for Printed Electronics; Donovan Sung notes the advantages and drawbacks of printing electronics via inkjet.

> Despite the promising results, inkjet printing has a number of disad vantages which prevent it from becoming an industrial production technique for printed electronics. First, it has a low throughput be cause of its slow print speed. Each ink droplet must be individually deposited through a printing dispenser, as opposed to roll-to-roll printing techniques where multiple drops can be printed at the same time. Second, inkjet printing tends to have short run lengths because the print heads are subject to clogging. Third, it cannot easily print a wide range of ink viscosities, which is necessary to properly optimize printed lines. Finally, it has a certain level of process instability be cause of statistical variation of droplets (Sung, 3).

While inkjet printing is a useful and cost effective way to print a small production of printed electronics, it simply cannot keep up with the speed and versatility of other commercial printing methods (Sung, 3).

For the mass production of printed electronics, gravure excels in the areas where inkjet falls short. Large gravure cylinders are capable of printing up to 2000 feet per minute while simultaneously depositing multiple drops of ink at a time, where an inkjet head prints one drop at a time (Sung, 4). Also, the cells on an etched gravure cylinder are constantly refilled with ink as the cylinder rotates within the ink trough below, thus sustaining long print runs and preventing against ink clogging, which is a common problem with the inkjet process. Gravure is also capable of printing a relatively wide variety of ink viscosities, or thicknesses of ink. Traditional gravure printing yields excellent quality and micro-engraving and micro-gravure printing are capable of an extremely high resolution, or very detailed product, necessary for high density circuits (Daetwyler). Gravure is mechanically simple process with fewer variables to control compared to other commercial printing methods, generally leading to a more consistent image (Sung, 5). These characteristics also help gravure compete against other high-speed printing processes such as lithography, flexography, and screen printing.

Controlling Gravure Quality

The quality of gravure is affected by several variables such as substrate properties, ink properties, and other mechanical parameters. Substrate properties and ink properties can have a large effect on the quality of the ink transferred. Substrate properties include smoothness (the flatness of the paper), compressibility (how much the paper compresses between rollers), porosity (a ratio of the volume of pores in the paper compared to the total mass), ink receptivity and wettability (how well the paper absorbs ink). Ink properties include ink chemistry (the chemical make-up of the ink), viscosity (the ink's resistance to flow), solvent evaporation rate (how quickly solvent evaporates from within the ink), and drying. Parameters of the gravure process also effect print quality, such as doctor blade angle and pressure, impression pressure, printing speed and the uniformity of the gravure cylinder diameter (Hrehorova, Kattumenu).

Cylinder Engraving Methods

When printing gravure, three different engraving methods can be used. These methods include electromechanical engraving, direct laser engraving and chemical etching with laser ablation. Each engraving method can produce various shapes and dimensions of gravure cells (Hrehorova, Kattumenu).

Electromechanical engraving is currently the most widely used engraving method. A diamond stylus is used to cut gravure cells directly into the copper cylinder as it rotates. Usually, one oscillation of the stylus produces one cell, and the volume of that cell depends on the amplitude of the oscillation, which is limited by the mechanical resonance of the stylus holder (Hrehorova, Kattumenu). Different tonal values are produced by engraving cells of various volumes. However, cells are limited to a fixed aspect ratio defined by the geometry of the diamond stylus. To produce lines, a row of dots is etched into the cylinder; therefore it is common to see ragged edges with electromechanical engraving (Hrehorova, Kattumenu).

In contrast, direct laser engraving does not involve a mechanical stylus at all. A laser beam is focused onto the surface of the gravure cylinder to create cells. Typically, gravure cylinders are coated with copper, but copper does not absorb laser energy, so a zinc layer is added to the surface of the cylinder for engraving purposes (Hrehorova, Kattumenu). Each pulse creates one cell and the cell volume is determined by the energy of that pulse. Direct laser engraving allows for a free selection of cell dimensions which helps to optimize ink transfer to the substrate (Hrehorova, Kattumenu).

Chemical etching in the final method used for cylinder engraving. Laser technology is also used in this process by imaging the mask layer, or creating what area will be engraved, prior to chemical etching. In the past, gravure was based on a film analog exposure and developing of the mask layer followed by chemical etching. Today, laser ablation is used, so no developing is needed (Hrehorova, Kattumenu). The amount of time that the etchant is in contact with the copper surface of the gravure cylinder controls the cell depth. In general, each cell produced has the same depth, so tonal variation is achieved by controlling the diameters of the etched cells (Hrehorova, Kattumenu).

For direct laser engraving and chemical etching with laser ablation, the resolution of engraving is limited by the diameter of the laser beam focus.

> With a direct laser imaging system, a minimum beam size of about 40 microns, [or 40 millionths of a meter], is used and, therefore, the minimum line width is about 40 microns. Indirect laser systems use a laser beam split into four beams of equal power (sufficient to ablate the mask resist) and typically work with a beam diameter of 10-20 microns for gravure applications. The minimum line width is, there fore, also about 10-20 microns, or a little more due to the sidewall etch ing (Hrehorova, Kattumenu).

This allows for a much thinner line to be printed if chemical etching with laser ablation is used. The capability of printing such thin lines makes gravure a viable method for the mass production of printed electronics (Hrehorova, Kattumenu).

Consistency of Ink Lines

While the gravure process is known for superior image quality, the etched cells struggle to produce a consistent ink line. The main challenge for gravure printed electronics is producing extremely thin lines accurately, which can be necessary for the electrical function of the printed device. Some electronic structures require conductive lines less than 20 microns wide (Sung, 26). There are two methods in gravure for printing solid lines: printed gravure lines, where a series of separate cells are etched closely together to form lines, or intaglio trenches, where a continuous trench is etched into the gravure cylinder. In his technical report, Donovan Sung evaluated the usability of both cells and trenches for printing small conductive lines (Sung, 26).

Printed gravure lines can show three types of printed line behavior. First, the drops can spread far enough apart to form discrete dots. Second, ink dots only partially intersect, resulting in “scalloped” or “saw-toothed” lines that can be narrower than the width of the individual drops. Lastly, the individual drops can form a smooth and continuous line. This can occur when the spacing between the cells is optimized, or when the ratio of drop spacing to landed drop radius is 1:10. The drop spacing is the distance between the centers of neighboring drops (Sung, 24).

Intaglio trenches are another method that can be used in gravure to print continuous lines. They remove the need of optimizing drop spacing and drop radius and can theoretically be scaled down to very small cell widths without worrying about cell emptying (Sung, 34). Intaglio trenches do have one very important defect that should not be overlooked. Trenches that are etched parallel to the print direction often show a “pick out” effect, meaning that the ink simply never transfers to the paper or substrate. However, pick out does not occur in trenches that are etched horizontally to the printing direction. Research suggests that this is because of the fluid flow within the trenches (Sung, 34). Overall, intaglio trenches have a greater variation in printed width uniformity compared to gravure printed lines, and typically print much wider lines. When the trench width is decreased, the printed line width only slightly decreases and can never reach a width of less than 20 microns, needed for some forms of printed electronics. Therefore, the best method for printing solid, narrow and continuous lines in gravure is to print individual cells with appropriate spacing (Sung, 35).

Electrical Resistance and Ohm’s Law

Although the consistency of ink lines is important for conducting electrical current; the length, width and height of the ink line also need to be controlled to support the flow of electrons throughout the ink line. In electricity, resistance is a property of an electrical conductor where it opposes the flow of electrons (Columbia Electronic

Encyclopedia). Voltage is described as the difference in potential energy between any two points in a circuit (Johnson, Roberts).

Ohm's Law states that the electric current (i) is equal to the applied voltage (v) divided by the resistance (r), or i = v/r (Columbia Electronic Encyclopedia). The resistance of electrical conductors can be controlled by three factors, conductor length, width, and height. Two wires, or in the case of printed electronics, conductive ink lines, that all have the same width and height can vary in resistance according to their length. The longer wire, or ink line, will have a greater resistance. If two wires, or ink lines, are of the same length, the resistance decreases as the thickness increases (thickness = length x width). In other words, thicker wires, or ink lines, allow more electrons to flow through them, thus the electrical current is increased (Johnson, Roberts).

Developments in Printed Electronics

Several new developments are occurring in the market and technology for printed electronics. Such developments include the use of mixed printing technologies, advancements in organic light emitting diodes (OLED) and radio frequency identification (RFID) tags, and the continued experiments with copper and other conductive inks (Harrop).

The employment of mixed printing technologies when producing printed electronics is becoming increasingly popular. These include combinations of micro-gravure, screen and ink-jet printing. New developments in toys and Internet interactive gaming cards make the use of screen printed electrodes and gravure printed ferroelectric memory polymers (Harrop).

Kodak holds the majority of patents on the latest OLED materials (Harrop). OLEDs are a thin and light display technology that does not require backlights. AMOLED, or active matrix organic light emitting diodes, are being experimented with for the use in large to medium displays including televisions (Harrop). Takatoshi Tsujimura, Senior Director of OLED Product Development for Kodak Japan Ltd concludes that medium to large AMOLED displays can be made by a combination of low risk technologies (Harrop).

Sunchon University in Korea has had great success in printing complete RFID tags using regular printing equipment. RFID tags can be used in products, animals, or even people for identification and tracking. A large market is seen in retail for inventory purposes. Sunchon University's RFID tags use inorganic semiconductors and dielectrics. To reduce cost, paper substrates are beginning to be of interest (Harrop).

With the expensive price of silver, other conductive metals need to be used as viable ingredients for metal based inks. Copper based inks are an option, though the corrosion on the copper poses a challenge. Hitachi Chemical has also announced organic insulating inks, suitable for printing resistors (Harrop).

Summary

Developments in printed electronics are opening new markets for traditional printing processes. While inkjet printing is currently used most frequently for the testing of printed electronics, gravure has more potential to become a means of production for the mass production of printed electronics. The quality of gravure printing can be affected by several variables, but many techniques can be used to control quality such as engraving techniques and optimizing the drop spacing ratio. Electrical resistance must also be taken into account for the conducting of electrical current within gravure ink lines. Gravure is an ideal production method for large quantities of high quality prints. Theoretically, gravure's ability for extremely fast, high resolution printing makes it an ideal candidate for the mass production of printed electronics.

Chapter 3 Research Methods

Certain variables may have an effect on the electrical function of printed electronics. This study is specifically interested in the capabilities of the gravure printing process to print conductive ink lines and the factors effecting how these lines are produced, as well as the applications that gravure would be best suited to manufacture. Two research methods were used to complete this study including secondary research and elite and specialized interviewing.

Secondary research involves analyzing previously published studies and literature to gain a better understanding of the topic being analyzed. The researcher must locate, gather, and interpret facts from previously published information and attempt to draw conclusions about the research subject.

Elite and specialized interviewing requires the interviewer to ask precise, open-ended questions, allowing the interviewee to establish a perspective on the subject. This type of interviewing allows for different responses between interviewees as comprehensibility, plausibility and consistency is sought, rather than a duplication of responses. It is best not to have a prepared list of questions or take notes during the interview, but rather record the interview to allow conversation to flow naturally while still capturing all of the relevant information (Levenson, 22-23).

By using secondary research, one aims to understand gravure's capabilities of printing conductive ink line. Past research projects and literature were analyzed to determine the capabilities of gravure ink lay-down and how the gravure process affects the electrical current of printed electronics.

One of the documents that was reviewed was a study undertaken by the Center of Ink and Printability Research at Western Michigan University. The study was published in GravurEzine in March 2009 and titled *Gravure Printed Features for Printed Electronics.* In this study, Alexandra Pekarovicova, Erika Hrehorova, Paul D. Fleming, Marian Rebros, and Margaret K. Joyce modify a flexographic press to print in a gravure configuration, and use this press to research gravure printed electronics.

Another document that was reviewed was a technical report from the Electrical Engineering and Computer Sciences Department of the University of California, Berkeley titled *Roll Printed Electronics: Development and Scaling of Gravure Printed Techniques.* In December 2009, Alejandro De la Fuente Vornbrock designed a custom table-top gravure press to make laboratory testing possible and cost-effective.

Two studies from the University of Oulu in Finland were also examined. The first was titled *Gravure Printing of Conductive Particulate Polymer Inks on Flexible Substrates* by Marko Pudas, Niina Halonen and Jouko Vähäkangas from Microelectronics and Physics Laboratories in 2005. In this study, the roto-gravure process was used and conductor line qualities were characterized for different substrates. The qualities include resistance, yield as a function of line width, coil inductance, folding endurance, adhesion, printed antenna properties and maximum current density.

The second study from the University of Oulu in Finland was titled *Gravure Offset Printing of Polymer Inks for Conductors*. In 2003, as part of the Microelectronics Laboratory and EMPART Research Group of Infotech Oulu, Marko Pudas, Juha Hagberg, and Seppo Leppävuori studied ink curing, or drying, and electrical properties of polymer inks that were printed using a gravure press.

Elite and specialized interviewing was also be used as a research method. Two professors within the graphic communication department at Cal Poly have been involved in research in the field of printed electronics: Dr. Xiaoying Rong and Dr. Malcolm Keif. Both of these professors were questioned to establish the major trends that are emerging in gravure printed electronics. Questions for the interviewees included:

- What is your area of study within printed electronics?
- How do you believe that gravure will impact the field of printed electronics in the future?
- What properties of gravure do you feel will help or impede the use of gravure for production of printed electronics?
- What specific electronic products do you believe that gravure would be an ideal production method for?

These questions were aimed at understanding the print side of printed electronics as well as seeing where the gravure fits into the printed electronics world.

A professor from Cal Poly's Electrical Engineering department, David Braun was also interviewed to determine the structural characteristics necessary to print a product that is capable of conducting electricity. Professor Braun has been researching new applications for organic semiconducting polymers. Questions for the interviewee included:

- What are the basic structural characteristics needed for an electrical device?
- Would you explain Ohm's Law, and how that might affect conductive ink that is printed on a flexible substrate?
- What is an IR drop, and how does it affect electrical current?
- What do you see happening in the future for printed electronics?

After performing secondary research and elite and specialized interviewing, the results of the research were explored. Capabilities of gravure ink lay-down were examined to determine the effect on the production of a conductive ink line and the products that gravure is best suited to produce. Conclusions were drawn exploring the possibilities for gravure in the future of printed electronics.

Chapter 4 Results

Research Study: *Gravure Printed Features for Printed Electronics*

In the study *Gravure Printed Features for Printed Electronics*, researchers from Western Michigan University tested three different types of gravure configurations; offset gravure, direct gravure with an open pan and inking roll, and direct gravure with an enclosed doctor blade chamber. Two conductive inks were used including a nanoparticle silver gravure ink and a water-based silver flake ink. Both were printed on commercial label paper as well as 2μm (2 microns) thick polyethylene terephathalate (PET) film.

The three gravure configurations produced very different results. When the metering roll with open inking pan was used, premature evaporation of the ink was noticed, requiring ink viscosity to be constantly adjusted by the addition of solvent. In the enclosed direct gravure configuration, some ink dots were missing and were not successfully transferred to the substrate. With the offset gravure process, all ink dots were transferred but many showed a distorted shape.

In the attempt to print a 40μm wide line, the effect of impression pressure was tested among the gravure configurations. Direct gravure produced the best fidelity of line width, and offset gravure produced the worst. When the highest impression pressure was used, all gravure configurations experienced line widening. The results of the printed line width and percent gain for each process are shown in Table 1.

Table 1: Line Widening of a 40μm Line

	Printed Line Width	Percent Gain
Offset Gravure	98±8μm	145%
Direct Gravure	62±4μm	55%

Other factors such as ink viscosity and print direction were shown to have an effect on line fidelity. Higher ink viscosity combined with high impression pressure resulted in the best line width (50.7±4μm for a 30μm nominal line). Lines printed parallel to the print direct showed better line fidelity than those printed perpendicular to the rotating cylinder.

Research Study: *Roll Printed Electronics: Development and Scaling of Gravure Printing Technologies*

This study was conducted by the University of California, Berkeley in the Electrical Engineering and Computer Sciences department. Alejandro De La Fuente Vornbrock examined the differences between printing dots, gravure-patterned lines and intaglio trenches with several types of conductive inks. A print speed of 0.1m/s was used to help maintain a stable printing process. All samples were printed on polyethylene terephthalate (PET).

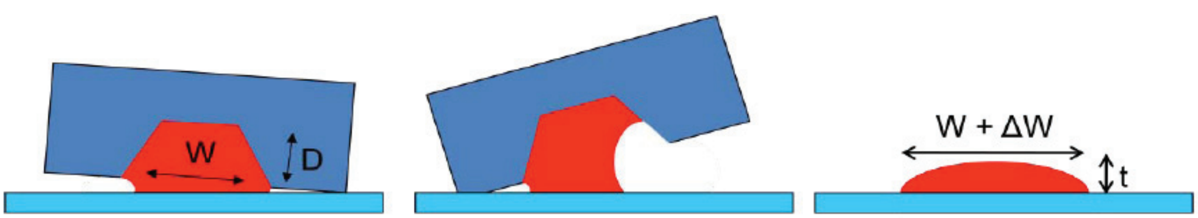
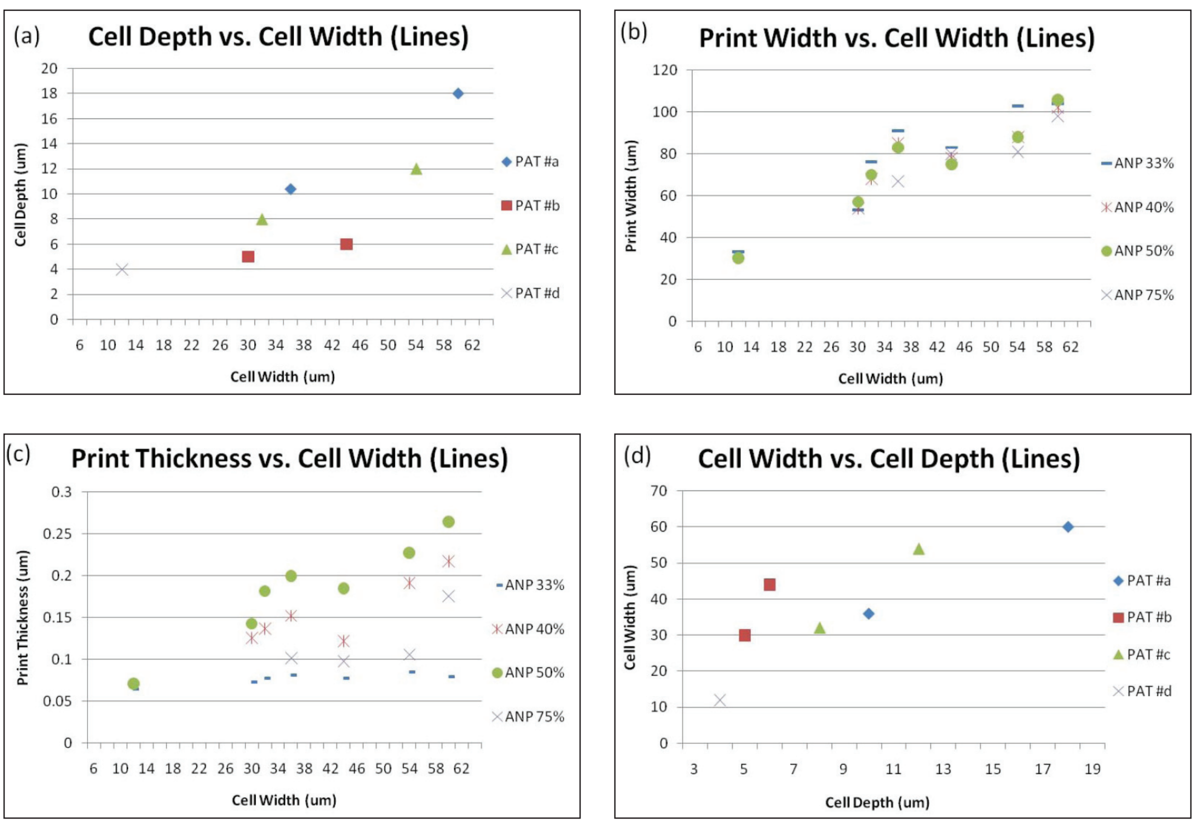


Figure 1: Schematic of ink being removed from gravure cells during printing (De la Fuente Vornbrock)

As shown in this study, the ink is never completely emptied from the cell. Proportionately, smaller cells empty less ink than larger cells. The amount of ink pulled from the cell can be affected by the surface energy of the substrate. Substrates with higher surface energy tend to adhere better to the ink causing more complete cell emptying. Print speed also affects cell emptying, as it determines how much sheer is applied to the ink. At high printing speeds, inks with higher viscosity have a greater resistance to sheer, causing cell-emptying problems.

This study also showed the effects of viscosity on line quality. If ink is too viscous, ink drops will result in lines with poor uniformity of width and thickness. Low viscosity inks can create lines that are too thin to be conductive. Optimizing ink viscosity helps to create thin, uniform, and straight lines with maximum thickness. Usually, wider lines tend to produce more uniform print thickness, because they allow more time for capillary flow, giving the individual drops time to smooth out.



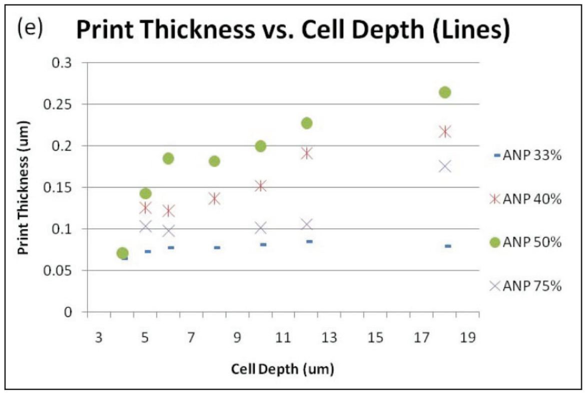
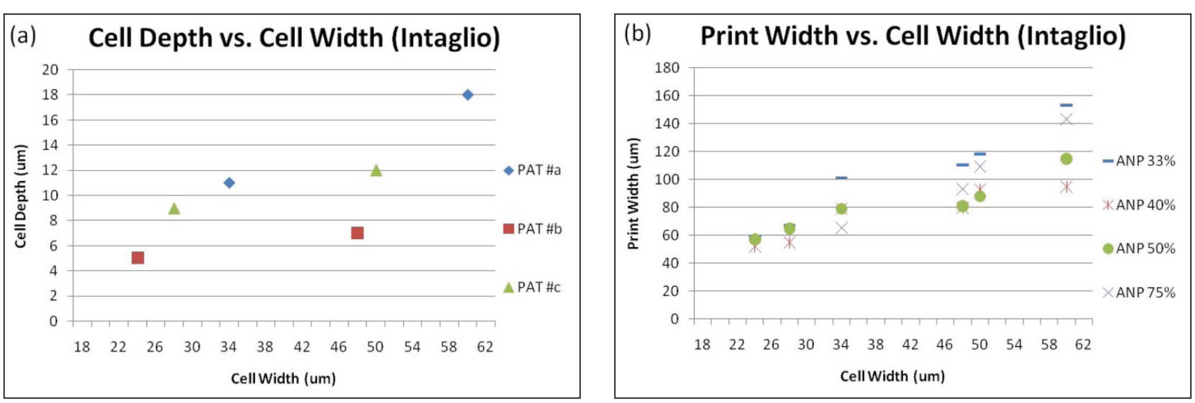


Figure 2: Relationship of cell depth and width to print lines with gravure patterns for different inks (De la Fuente Vornbrock)

Both gravure patterned lines and intaglio trenches were tested. The quality of the printed line and the variables affecting it were examined. With gravure patterned lines, line width is dependent on cell width as well as cell depth. Deeper cells produce thicker and wider lines. As shown in the graphs above, lines typically print 5μm wider and 10μm thicker than their corresponding dots etched into the cylinder. Gravure patterned lines may cause inconsistent line thickness and width, leading to yield problems and high resistance.

When printing intaglio trenches, a larger amount of ink per unit length can be achieved compared to gravure patterns, as there is no loss of volume to cell walls and spaces. However, with intaglio trenches, other drawbacks can occur such as pick-out and directional effects. Pick-out is noticed in trenches that are etched parallel to the print direction, caused by the flow of ink within the trench.



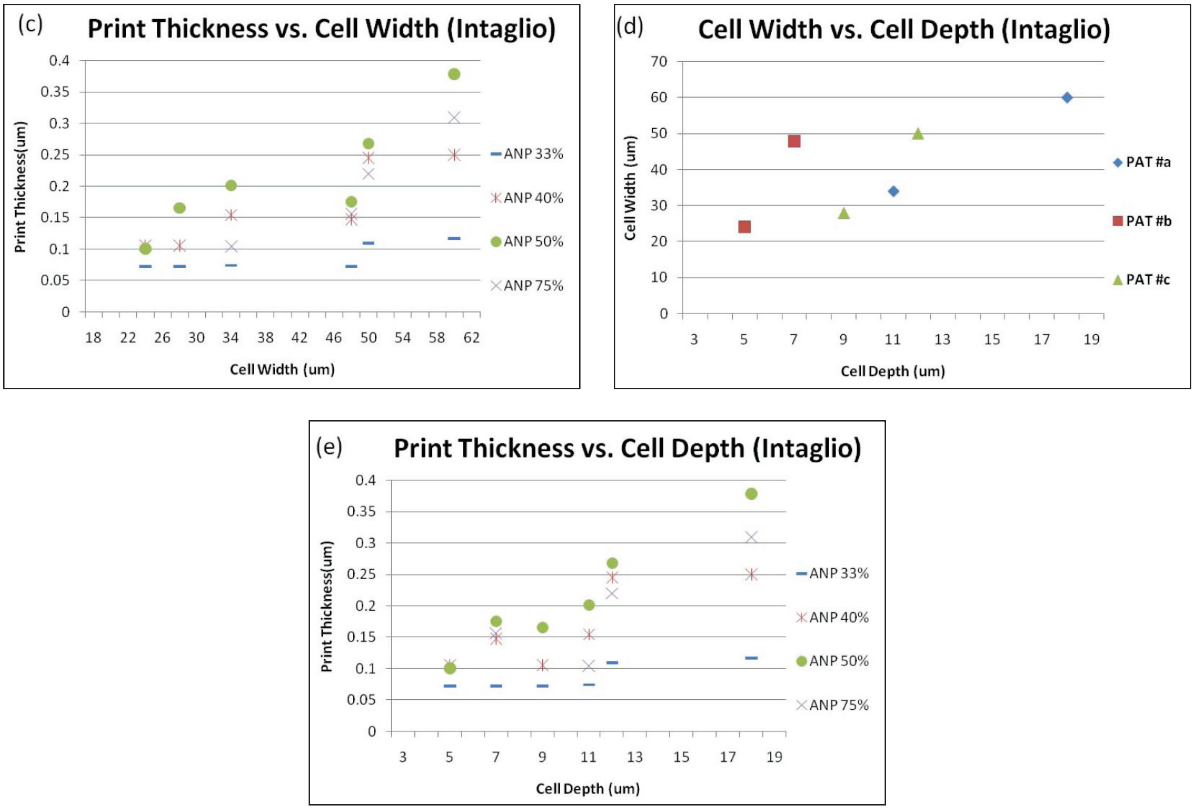


Figure 3: Relationship of cell depth and width to print thickness for intaglio trenches for different inks (De la Fuente Vornbrock)

The figure above shows the relationship between intaglio depth and width compared to print width and thickness. The relationship is linear with a dependence on cell depth. The print thickness is also linearly dependent on cell depth with a small correlation to cell width. Generally, intaglio trenches print wider lines than those produced by gravure patterned lines.

Research Study: *Gravure Printing of Conductive Particulate Polymer Inks on Flexible Substrates*

In this study, researchers from the University of Oulu, Finland, printed gravure test patterns of high-conductivity inks containing particles of silver to determine resistance with different line widths and lengths. For comparison, similar patterns were printed by a rotary-screen process. Chemical etching was used to create 20-60μm deep grooves into the cylinder. This study determined that the maximum line ink cross-section is not the best measurement of a conductor, but rather the line cross-section averages give a better indication of conductivity.

When using printing methods, maximum conductivity can be difficult to achieve. For high conductivity, a thick ink layer is needed. This can be obtained with high viscosity and a silver content up to 80%. However, specifications for gravure printing require a lower ink viscosity and a higher solvent content, allowing silver content to be only as high as 60-70%.

During testing, the 20-60μm deep grooves produced ink lines that were 4-7μm thick. For printing the thickest ink layer, high pressure and a slow printing speed are preferred. Although more ink is printed from wider grooves, significant line widening occurs as the ink spreads, causing a disadvantage. Both intaglio trenches and gravure-patterned lines were tested in this study. A lower resistance and a thicker ink later was seen in the intaglio trenches.

Research Study: *Gravure Offset Printing of Polymer Inks for Conductors*

Researchers from Oulu, Finland used offset gravure in this study. The gravure grooves were used to transfer the ink to a pad, and the pad was used to transfer the ink to the substrate. The goal of the experiment was to decrease the resistance of conductor lines.

Two inks, ink A and ink B, were tested, with ink B having a higher solid particle content. Ink A had a high viscosity and dried very rapidly, causing the ink to block the grooves in the gravure cylinder. Oil was added to the ink, improving printability but decreasing the highest ink laydown. The printing environment was altered in order to achieve the best printing parameters possible for the inks to be studied.

During testing, a minimum square resistance of 20mΩ/square was achieved for a 300μm wide line and a square resistance of 28mΩ/square was achieved for a 150μm wide line. Both lines were between 7-8.5μm thick.

Personal Interview: Dr. Xiaoying Rong

Dr. Xiaoying Rong explained her opinion on gravure process capabilities for printed electronics and the future gravure has in the market. Dr. Rong has been specifically doing research with screen printed electronics, but the coarse resolution of the screens makes printing devices with fine features impossible. Dr. Rong explained issues concerning ink surface uniformity. With any printing process, ink film is expected to level out, but sometimes due to the formulation of the ink, a lack of surface uniformity is produced. With gravure, peaks and valleys are noticed on the surface of the ink due to the cells on the gravure cylinder that carry the ink. This can cause problems with electrical resistance. In order to achieve a thick ink film, sometimes several layers need to be printed on top of underlying layers. This "double hit" of ink increases problems with surface uniformity.

Dr. Rong believes that all types of electronics cannot be achieved through printing methods. It is unlikely that high power devices will be manufactured on a printing press. Currently, the demand for printed electronics is not very high, so a slower speed will suffice. Gravure strengths compared to other printing processes are in speed and resolution. In the future, Dr. Rong believes that the best option for gravure will be to add function to existing printing. This may include simple electronic products such as electrolumiescent wallpaper. Also, gravure printed electronics can be included into "smart packaging" for uses like tracing and detecting. The production of transistors or other full-on electronic devices probably won't happen without continuous improvement to the process and engraving methods.

Personal Interview: David Braun

David Braun is a professor in the Electrical Engineering department at Cal Poly, and has been doing research with organic light emitting diodes (OLED). Professor Braun explained that the conduciveness of printed electronics can be limited by the materials resistivity. If the material obeys Ohm's law, a voltage can be applied and current measured or a current can be applied and voltage measured. Resistivity and resistance are related but they are not the same thing. Below is an equation showing their relationship.

Resistance = (resistivity x length)/cross-sectional area

Professor Braun also further commented on Dr. Xiaoying Rong's concern with rippled ink surfaces. He explained that a thick uniform ink surface would have the lowest resistance and a thin uniform ink surface would have a higher resistance. However, a rippled ink surface would cause a resistance even higher than a thin uniform surface.

Personal Interview: Malcolm Keif

Dr. Malcolm Keif has been studying how printing processes can lay down functional inks to be useful, including the characteristics of each method and how the ink film it lays down is characterized. When asked about gravure's impact on printed electronics, Dr. Keif commented that gravure has the ability to lay down a thick layer of ink. The biggest advantage that gravure has is the ability to work with a wide range of ink viscosities. This could allow thicker inks, with better conductive solid densities, to be used at slow printing speeds. A slower speed is necessary to allow more viscous ink time to enter and be removed from the cell during printing.

Dr. Keif also commented on the drawbacks of gravure for printing electronics, namely the electromechanical engraving process. Electromechanical engraving is not good for engraving sharp edges, and creates serrated edges on printed lines. Typically, electromechanical engraving changes the cell depth to apply more ink for graphic tonality. When printing electronics, a consistent ink film thickness is desirable for both wide and thin lines. With electromechanical engraving, this would require a consistent cell depth, which is not typically how it's done. This is not a problem for acid etching or laser engraving, as cell depth can be controlled.

As for the future of printed electronics, Dr. Keif does not believe that any single printing process will be good for all functional layers of any product. Everything will be created from hybrid processes. Gravure's most likely candidates are batteries, solar cells, and OLED lighting and signs. These products are the least detailed and have low power requirements. Dr. Keif has a positive outlook and believes that the processes that will ultimately "win" in printed electronics haven't been invented yet, or at least have not morphed to where they need to be.

Chapter 5 Conclusions

After completing the research, it is clear that gravure has many advantages as well as drawbacks in the production of printed electronics. As a mechanically simple process, there are less process variables to control compared to other printing processes. The use of an etched chrome-plated cylinder lends itself to solvent compatibility, allowing a broad range of inks to be printed with gravure. Gravure is also capable of laying down a thicker ink film, necessary for the flow of electrons through conductive ink.

During the production of gravure printed electronics, several print variables can affect the fidelity of conductive lines. In general, increased pressure causes line widening on the substrate. The best line fidelity can be achieved with high viscosity ink, high pressure, slow print speed, and lines etched parallel to the print direction. The slow print speed allows time for the ink to fill and be extracted from the cells on the cylinder, while more viscous ink helps to decrease dot gain and maintain ink height. Less print problems are seen when lines are etched parallel to the print direction.

One of the most important print variables for printed electronics is ink surface uniformity. To create the least resistance through a conductive ink line, a high ink height is needed with uniform thickness. Printing with gravure patterned lines versus intaglio trenches will produce a less uniform ink surface. With gravure patterned lines, more ink is laid down compared to the same width intaglio trench. The individual cells create scalloped edges and non-uniform ink surface. As multiple layers of ink are added, the problem is increased. A wavy ink surface increases the resistance of the printed ink line when compared to a uniform surface.

Printing intaglio trenches instead of gravure patterned lines helps to maintain a more uniform surface, but other problems are of concern. A severe “pick out” effect can be observed when intaglio trenches are etched perpendicular to the print direction, causing gaps in ink flow. This limits the patterns trenches can be etched in to produce successfully printed lines.

It is unlikely that any specific printing process will completely dominate the production of a single electrical product. Gravure will definitely be a large portion of a hybrid manufacturing process that creates low power devices. Printed electronics are not going to be high voltage or high density electronics, as the processes are not capable of printing the small and detailed requirements. Gravure printed electronics will mostly likely include batteries, photovoltaics, and function added to existing printed products. This may include areas such as smart packaging or electroluminescence products.

As the demand for traditional print declines, printers look for new ways to reinvent their business. Functional printing will be a part of the future, but it is unlikely that it will completely transform the way the majority of electronics are manufactured.

References

Braun, David. Personal Interview. May 5, 2010.

Columbia Electronic Encyclopedia, 6th Edition. October 1, 2009. Retrieved online through Academic Search Elite February 17, 2010.
<http://search.ebscohost.com/login.aspx?direct=true&db=afh&AN=39025440&site=ehost-live>

Daetwyler R&D Corporation. "Printed Electronics." Daetwyler R&D Corporation. Retrieved online January 31, 2010.
<http://www.daetwyler-rd.com/doc/Printed_Electronics_sales-sheet.pdf>

De la Fuente Vornbrock, Alejandro. "Roll Printed Electronics: Development and Scaling of Gravure Printing Technologies." December 29, 2008. University of California Berkeley. Retrieved online March 18, 2010.
<www.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-191.pdf>

Harrop, Peter. "New Trends in Printed Electronics." Printed Electronics World. October 5, 2009. Retrieved online January 31, 2010.
<http://www.printedelectronicsworld.com/articles/new_trends_in_printed_electronics_00001745.asp>

Hrehorova, Erika, and Ramesh-Chandra Kattumenu. "Evaluation of Gravure Print Forms for Printed Electronics." GravurEzine. March 2007. Retrieved online January 29, 2010.
<http://www.gravurexchange.com/gravurezine/0702-ezine/hrehorova.htm>

Johnson, Phil, and Shaun Roberts. "Electric Circuits." University of Durham School of Education. 2006. Retrieved online February 17, 2010.
<http://www.dur.ac.uk/p.m.johnson/electric_circuits/electric_circuits.htm>

Keif, Malcolm. Personal Interview. May 12, 2010.

Lawler, Brian. "Digital Printing and Emerging Technologies." April 2009. Class lecture given at California Polytechnic State University, San Luis Obispo.

Levenson, Harvey Robert, Ph.D. Some Ideas About Doing Research in Graphic Communication. 2001. Atascadero, CA: The Good Neighbor Press and Services.

Pekarovicova, Alexandra, Erika Hrehorova, Paul D. Fleming, Marian Rebros, and Margaret K. Joyce. "Gravure Printed Features for Printed Electronics." GravurEzine. March 2009. Retrieved online February 27, 2010.
<www.gravurexchange.com/pdfs/GravurEzine-0902.pdf>

Pudas, Marko, Juha Hagberg, and Seppo Leppävuori. "Gravure Offset Printing of Polymer Inks for Conductors." Progress in Organic Coatings, 49 (4), pp. 324-335. 2004. Retrieved online March 1, 2010.
<http://www.sciencedirect.com/science/article/B6THD-4BDC95F-1/2/d8469e89c1e1e8d6d9918eaff30608c4>

Pudas, Marko, Niina Halonen, Päivi Granat, and Jouko Vähäkangas. "Gravure Printing of Conductive Particulate Polymer Inks on Flexible Substrates." Progress in Organic Coatings, 54 (4), pp. 310-316. 2005. Retrieved online March 1, 2010.
<http://www.gravurexchange.com/gravurezine/0801-ezine/pudas.htm>

Rong, Xiaoying. Personal Interview. May 5, 2010.

Sung, Donovan. "Gravure as an Industrially Viable Process for Printed Electronics." May 23, 2008. University of California Berkeley. Retrieved online January 29, 2010.
<http://www.eecs.berkeley.edu/Pubs/TechRpts/2008/EECS-2008-70.pdf>